METHOD AND AN APPARATUS FOR USE OF CODES IN MULTICAST TRANSMISSION

BACKGROUND OF THE INVENTION

I. Field of the Invention

[1001]   The current invention relates to the field of communications. More particularly, the present invention relates to the use of codes in multicast transmission.

II. Description of the Related Art

[1002]   Communication systems have been developed to allow transmission of an information signal from an origination station to one or more physically distinct destination stations. In transmitting the information signal from the origination station over a communication channel, the information signal is first converted into a form suitable for efficient transmission over the communication channel. As used herein, the communication channel comprises a single path over which a signal is transmitted. Conversion, or modulation, of the information signal involves varying a parameter of a carrier wave in accordance with the information signal in such a way that the spectrum of the resulting modulated carrier is confined within the communication channel bandwidth. At the destination station the original information signal is replicated from the modulated carrier wave received over the communication channel. Such a replication is generally achieved by using an inverse of the modulation process employed by the origination station.

[1003]   Modulation also facilitates multiple-access, i.e., simultaneous transmission and/or reception of several signals over a common communication channel. Multiple-access communication systems often include a plurality of remote subscriber units requiring intermittent service of relatively short duration rather than continuous access to the common communication channel. Several multiple-access techniques are known in the art, such as Time Division Multiple-Access (TDMA), Frequency Division Multiple-Access (FDMA), and Amplitude

Modulation (AM). Another type of multiple-access technique is used in a Code Division Multiple-Access (CDMA) spread spectrum system that conforms to the "TIA/EIA/IS-95 Mobile Station-Base Station Compatibility Standard for Dual-Mode Wide-Band Spread Spectrum Cellular System," hereinafter referred to as the IS-95 standard. The use of CDMA techniques in a multiple-access communication system is disclosed in U.S. Patent No. 4,901,307, entitled "SPREAD SPECTRUM MULTIPLE-ACCESS COMMUNICATION SYSTEM USING SATELLITE OR TERRESTRIAL REPEATERS," and U.S. Patent No. 5,103,459, entitled "SYSTEM AND METHOD FOR GENERATING WAVEFORMS IN A CDMA CELLULAR TELEPHONE SYSTEM," both assigned to the assignee of the present invention and incorporated herein by reference.

[1004] A multiple-access communication system may carry voice and/or data. An example of a communication system carrying both voice and data is a system in accordance with the IS-95 standard, which specifies transmitting voice and data over the communication channel. A method for transmitting data in code channel frames of fixed size is described in detail in U.S. Patent No. 5,504,773, entitled "METHOD AND APPARATUS FOR THE FORMATTING OF DATA FOR TRANSMISSION," assigned to the assignee of the present invention. In accordance with the IS-95 standard, the data or voice is partitioned into code channel frames that are 20 milliseconds wide with data rates as high as 14.4 kbps. Additional examples of communication systems carrying both voice and data are communication systems conforming to the "3rd Generation Partnership Project" (3GPP), embodied in a set of documents including Document Nos. 3G TS 25.211, 3G TS 25.212, 3G TS 25.213, and 3G TS 25.214 (the W-CDMA standard), or "TR-45.5 Physical Layer Standard for cdma2000 Spread Spectrum Systems" (the IS-2000 standard).

[1005] An example of a data only communication system is a high data rate (HDR) communication system, such as the communication system disclosed in co-pending application serial number 08/963,386, entitled "METHOD AND APPARATUS FOR HIGH RATE PACKET DATA TRANSMISSION," filed 11/3/1997, assigned to the assignee of the present invention. The HDR communication system defines a set of data rates, ranging from 38.4 kbps to

2.4 Mbps, at which an origination terminal (Access Point, AP) may send data to a receiving terminal (Access Terminal, AT).

[1006]   The information signal to be exchanged among the terminals in a communication system is often organized into a plurality of packets. For the purposes of this description, a packet is a group of bytes, including data (payload) and control elements, arranged into a specific format. The control elements comprise, e.g., a preamble and a quality metric. The quality metric comprises, e.g., Cyclical Redundancy Check (CRC), parity bit(s), and other types of metric known to one skilled in the art. The packets are usually formatted into a message in accordance with a communication channel structure. The message, appropriately modulated, traveling between the origination terminal and the destination terminal, is affected by characteristics of the communication channel, e.g., signal-to-noise ratio, fading, time variance, and other such characteristics. Such characteristics affect the modulated signal differently in different communication channels. Consequently, transmission of a modulated signal over a wireless communication channel requires different considerations than transmission of a modulated signal over a wire-like communication channel, e.g., a coaxial cable or an optical cable. In addition to selecting modulation appropriate for a particular communication channel, other methods for protecting the information signal have been devised.   Such methods comprise, e.g., encoding, symbol repetition, interleaving, and other methods know to one of ordinary skill in the art.   However, these methods increase overhead. Therefore, an engineering compromise between reliability of message delivery and the amount of overhead must be made. Even with the above-discussed protection of information, the conditions of the communication channel can degrade to the point at which the destination station possibly cannot decode (erases) some of the packets comprising the message. In data-only communications systems, the cure is to re-transmit the non-decoded packets using an Automatic Retransmission reQuest (ARQ) made by the destination station to the origination station.

[1007]   Often a message is multicast transmitted by the origination station. For the purposes of this document, multicast transmission means transmission of a message that is intended to be received by a plurality of destination

stations. However, for the above-discussed reasons, the destination stations may fail to decode a subset of the message. Furthermore, subsets of packets that are not decoded may differ from one destination station to another destination station.

[1008] Based on the foregoing, there is a need in the art for a method and an apparatus for multicast transmission that allows each destination station to decode the destination station's faulty subset of packets, and to reconstruct the multicast message.

SUMMARY OF THE INVENTION

[1009] The present invention is directed to a method and an apparatus allowing each destination station to decode a multicasted message from an origination station. In one aspect of the invention, the origination station processes each of a plurality of data sets to generate a processed data set and a parity block for each data set, processes a plurality of the parity blocks to generate at least one packet; and transmits the plurality of processed data sets and the at least one packet. The destination station receives a plurality of packets comprising the message, and at least one other packet, decodes each packet of the plurality of packets comprising the message; and decodes each incorrectly decoded packet in accordance with the at least one other packet when a number of the incorrectly decoded packets is less than or equal to a pre-determined code distance.

[1010] In another aspect of the invention, the origination station processes each of a plurality of data sets to generate a processed data set and a parity block for each data set, transmits the plurality of processed data sets as packets, receives signals containing information about incorrectly decoded packets, and when the signals are received processes a plurality of the parity blocks to generate at least one packet; and transmits the at least one packet. The destination station decodes each packet of the received plurality of packets comprising the message; transmits a report containing at least one number; receives at least one packet in response to the report; and decodes the

incorrectly decoded packets in accordance with the received at least one packet.

BRIEF DESCRIPTION OF THE DRAWINGS

[1011]   **FIGS. 1A-1B** illustrate a block diagram of a communication system with shared redundancy;

[1012]   **FIGS. 2A-2D** illustrate a block diagram of a communication system with shared redundancy with punctured bytes;

[1013]   **FIG. 3** illustrates a method used by a j-th destination station to recover erased packets; and

[1014]   **FIG. 4** illustrates another method used by the j-th destination station to recover erased packets.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

[1015]   In order to compare performance of the methods and apparatus in accordance with different embodiments of the present invention, a concept of a baseline system is introduced.

Baseline System

[1016]   In a baseline system, each of N packets, comprising a message, is sent as an element of a code C_1, i.e., each packet is encoded by a code C_1. The code C_1 contains an amount of redundancy designed to satisfy message delivery with a probability $P_{C1Average}$ under certain, i.e., average, conditions of a communication channel. Furthermore, the code C_1 also has the property that the maximum number of packets organized into an N packet message that cannot be decoded correctly by a destination station is less than or equal to S with a probability P_{C1}. Consequently, when the variation in the condition of the

communication channel between the origination station and the particular destination station(s) degrades below the design criteria, a subset of the packets comprising the message fails to be decoded at the destination station(s).

[1017]   The amount of redundancy necessary to satisfy reliable message delivery under certain conditions of the communication channel is the only design requirement for selection of the code C_1. Thus, the code C_1 may be, e.g., an algebraic block code such as a Reed-Solomon code, a state machine code such as a convolutional or trellis code, a classical concatenated code, a serial/parallel concatenated turbo code, or a binary convolutional code, as well as other codes known to one skilled in the art.

[1018]   For the purposes of quantitatively comparing various methods used by a destination station to decode the packets comprising the message, it can be assumed without loss of generalization, that an input signal comprises N blocks of K bytes, which result in $(K+R_1)$ coded bytes when encoded with the code C_1. (The term byte as used in this document includes a 1-bit byte.) R_1 denotes number of additional byte, related to the number of the input signal bytes K. R_1 is the measure of the code C_1 redundancy. Therefore, in the baseline system, each of the N packets is transmitted as a sequence of $(K+R_1)$ bytes.

Automatic Retransmission reQuest

[1019]   To improve the performance of the baseline system, the non-decoded packets of the message may be re-transmitted using a modification of an ARQ. In such an ARQ arrangement, every destination station reports to the origination station a list of packets that were not decoded correctly. The origination station re-transmits every packet that appears on any of the lists. The process of reporting and re-transmitting is repeated until every destination station decodes all the packets of the message. The fractional overhead (FO) of the ARQ system is analyzed as follows. Let P_e denote the probability that at least one destination station fails to decode a packet sent as an element of the code C_1.

The average number of bytes (ANB) to be re-transmitted in order to deliver the message to all the destination stations is given by the following equation:

$$ANB = \frac{N \cdot (K + R_1)}{(1 - P_e)} \qquad (1)$$

Therefore, the fractional overhead relative to the baseline system (FO$_{ARQ}$) is:

$$FO_{ARQ} = \frac{P_e}{(1 - P_e)} \qquad (2)$$

Because the probability (1-P$_e$) decreases exponentially with an increase in the number of destination stations, the ARQ arrangement efficiency decreases with increasing number of the destination stations. Furthermore, a variable latency exists in this ARQ arrangement.

<u>Full Redundancy per Packet</u>

[1020]   Another approach allowing every destination station to decode all the packets in the message is to design the communication system in accordance with the worst-case condition of the communication channel.   In such an approach, each packet is encoded by a code C$_3$. The code C$_3$ is selected so that each encoded packet is decoded correctly with a probability P$_{C3}$ under the worst-case condition of the communication channel by every destination station. A relationship between a required probability of receiving the message P$_{Message}$ under the worst-case condition of the communication channel and the probability P$_{C3}$ is given by the equation:

$$P_{Message} \approx N \cdot P_{C3} \qquad (3)$$

[1021]   The assumption of the worst-case condition of the communication channel for every transmitted packet makes this scheme very inefficient. A measure of the inefficiency is the number of extra bytes transmitted as compared to the baseline system.   For the purposes of quantitatively characterizing this method it can be assumed, that K bytes of an input signal result in (K+R$_3$) coded bytes when encoded with the code C$_3$. One of ordinary

skill in the art recognizes that because the code C_3 is designed to deliver the message under the worst-case condition of the communication channel while the code C_1 was designed to deliver the message under average conditions of the communication channel, the amount of redundancy of the code C_3 is greater than the amount of redundancy of the code C_1. Consequently, the number of parity bytes R_3 is greater than the number of parity bytes R_1. This relationship is expressed as:

$$R_3 = R_1 + R_{13} \qquad (4)$$

where R_{13} is the number of extra parity bytes of the code C_3 in relation to the code C_1. Because R_2 extra bytes are transmitted per packet in this arrangement relative to the baseline system, the N packets comprising the message contain a total of NR_2 extra bytes relative to the baseline system. The fractional overhead (FO_{FRPP}) is:

$$FO_{FRPP} = \frac{R_{13}}{(K + R_1)} \qquad (5)$$

[1022] The amount of redundancy necessary to satisfy message delivery under the worst-case condition of the communication channel is the only design requirement on the code C_3. Thus, the code C_3 may be, e.g., an algebraic block code such as a Reed Solomon code, or a state machine code such as a convolutional or trellis code. The code C_3 may also be a classical concatenated code, a serial/parallel concatenated turbo code, or a binary convolutional code, as well as other codes known to one skilled in the art.

Shared Redundancy

[1023] FIG. 1A illustrates a conceptual block diagram of a communication system employing shared redundancy.

[1024] In one embodiment, a Data Source (DS) **102** generates an information signal to be multicasted. The information signal is divided into N blocks, each block comprising K bytes. The N blocks are provided to a first encoder (EC1) **104**, which encodes each of the N blocks with a code C_1, providing a packet comprising K+R_1 code bytes as shown in **FIG. 1A**. The code

C_1 is selected so that the maximum number of packets organized into an N packet message that cannot be decoded correctly by a destination station is less than or equal to S with probability P_{C1}.

[1025] The N blocks are also provided to a second encoder (EC2) **106**. Referring to **FIG. 1B**, in one embodiment, the i-th byte of each of the N blocks is combined to form an i-th input data block **120**. Each input data block **120** is then provided to the encoder **106**, which is a systematic block encoder **106** in one embodiment. For the purposes of this document, a systematic code comprises a permutation of information (systematic) bytes and parity bytes. Thus, a systematic code is defined by the following equation:

$$x = \pi(u, p) \qquad\qquad (6)$$

where: x is the coded signal;

π is a permutation;

u are systematic bytes; and

p are parity bytes.

The systematic block encoder **106** encodes each input data block **120** with a systematic code C_4 having a minimum distance greater than S, resulting in K encoded packets **122**. Each encoded packet **122** comprises N systematic bytes and N' parity bytes. In one embodiment, a systematic Reed-Solomon (RS) code with N' = S, which is guaranteed to have a minimum distance of (S+1), is used.

[1026] In another embodiment, the NK systematic bytes of the N packets are provided to a systematic block encoder **106**. The systematic block encoder **106** encodes the NK systematic bytes with a systematic code C_5. The systematic code C_5 is selected to be capable of correcting segments in the NK systematic bytes when each of the segments contains a maximum of S errors. A segment comprises the i-th systematic byte of each of the N packets. In one embodiment, a Reed-Solomon code having a minimum distance greater than KS is used.

[1027] The encoding by the encoder **106** results in NK systematic bytes and N'K parity bytes. The N'K parity bytes computed by the encoder **106** are provided to a third encoder (EC3) **108**. The encoder **108** encodes the N'K parity bytes with the code C_3. The code C_3 is selected so that a packet sent as an element of the code C_3 is decoded correctly with a probability P_{C3} by every destination station. A relationship between a required probability of receiving the message $P_{Message}$, the probability P_{C1}, and the probability P_{C3} is given by the following equation:

$$P_{Message} \approx P_{C1} + P_{C3} \qquad\qquad (7)$$

Therefore, given a reliability requirement for message delivery expressed in terms of $P_{Message}$, Equation (7) is used for selection of the codes C_1 and C_3.

[1028] The purpose of encoding the N'K parity bytes by the code C_3 is to deliver the encoded N'K parity bytes **122** with reliability expressed in terms of P_{C3}. Consequently, there is no restriction on the organization of the encoded N'K parity bytes **122**. Therefore, the encoded N'K parity bytes **122** may be organized in an arbitrary number of packets. Consequently, in one embodiment, the encoded N'K parity bytes **122** form one packet. In another embodiment, the encoded N'K parity bytes **122** are organized into a plurality of packets.

[1029] Referring back to **FIG. 1A**, the output signals of the encoder **104** and the encoder **108** are provided to a transmitter (TX) **110**. The transmitter **110** performs processing of the provided signals in accordance with a modulation scheme used. In one embodiment, the modulation is carried out in accordance with the requirements of a wireless communication channel. The transmitter **110** then transmits the N packets provided by the encoder **104** and the packet or packets provided by the encoder **108** over a communication channel **112**. Although a wireless communication channel is shown in **FIG. 1**, one of ordinary skill in the art recognizes that the communication channel **112** can be wire-like, e.g., a coaxial cable, an optical cable, etc. In such an embodiment, the

modulation is carried out in accordance with the requirements of the particular wire-like communication channel.

[1030] A receiver (RX) **114** receives the N-packet message and the packet or packets of the encoded N'K parity bytes **122** of **FIG. 1B**. The receiver **114** processes the packets in accordance with a demodulation scheme. Generally, an inverse of the modulation process employed by the transmitter **110** is used. The processed packets are provided to a decoder (DC) **116**. The decoder **116** decodes each of the N received message packets. As discussed, at most S of the N packets fail to decode. The decoder **116** then decodes the N'K parity bytes and uses the N'K parity bytes to reconstruct the non-decoded packets. The reconstruction may be carried out in accordance with any method known to one of ordinary skill in the art. For example, a method for a systematic Reed Solomon (RS) code is disclosed in Truong, T.-K., Jeng, J., H., and Hung, K.-CH., Inversionless Decoding of Both Errors and Erasures of Reed-Solomon Code. The decoded packets are provided to a data sink (DSK) **118**.

[1031] The Total Number of Bytes (TNB) transmitted by this scheme when RS is used is:

$$TNB = N \cdot (K + R_1) + N^{'} \cdot (K + R_3) \tag{8}$$

Because N'(K+R₃)=S(K+R₃) extra bytes are transmitted per packet relative to the baseline system, the fractional overhead (FO$_{SR}$) is:

$$FO_{SR} = (\frac{S}{N}) \cdot (1 + \frac{R_{13}}{(K + R_1)}) \tag{9}$$

Shared Redundancy with Punctured Bytes

[1032] **FIG. 2A** illustrates a conceptual block diagram of a communication system employing shared redundancy with punctured bytes.

[1033] In one embodiment, a Data Source (DS) **202** generates an information signal to be multicasted. The information signal is divided into N blocks, each block comprising K bytes, and the blocks are provided to an

encoder (EC_1) **204**. The encoder **204** encodes each of the N blocks with a code C_1, providing a packet comprising $K+R_1$ code bytes as shown in **FIG. 2B**. The code C_1 is selected so that the maximum number of packets organized into an N-packet message that cannot be decoded correctly by a destination station is less than or equal to S.

[1034] The encoder **204** also computes R_2 parity bytes of a code C_2 for each of the N blocks, providing a packet structure illustrated in **FIG. 2C**. The packet structure encoded by the code C_2 comprises $K + R_1$ coded bytes (i.e., a structure of a packet encoded by the code C_1) appended by the R_2 parity bytes. Consequently, the code C_2 is an extension of the code C_1. In other words, the code C_1 is a punctured version of the code C_2. The code C_2 is selected so that a packet sent as an element of the code C_2 is decoded correctly with a probability P_{C2} by every destination station.

[1035] One of ordinary skill in the art recognizes that different apparatuses and methods accomplish encoding of the information signal to provide the packet structures shown in **FIG. 2B** and **2C**. However, as long as the particular apparatus and method provide the packet structures of **FIG. 2B** and **2C**, a selection of a particular apparatus and method is a matter of implementation.

[1036] The NR_2 parity bytes computed by the encoder **204** for the N-packet message are further encoded. In one embodiment, illustrated in **FIG. 2D**, the i-th parity byte of each of the N packets is combined to form an i-th input data block **220**. Each input data block **220** is provided to a systematic block encoder (EC_2) **206**. The systematic block encoder **206** encodes each input data block **220** by a systematic code C_4, having a minimum distance greater than S, resulting in R_2 encoded packets. Each encoded packet comprises N systematic bytes and N' parity bytes. In one embodiment, a systematic Reed-Solomon code with N' = S, which is guaranteed to have a minimum distance of (S+1), is used. Although **FIG. 2D** illustrates the input data bytes **220** to be encoded in parallel, one of ordinary skill in the art recognizes that such an illustration is for pedagogical reasons only, and other arrangements, e.g., serial encoding, are possible.

[1037]   In another embodiment (not shown), the NR_2 parity bytes are provided to the systematic block encoder **206**. The systematic block encoder **206** encodes the NR_2 parity bytes with a systematic code C_5. The systematic code C_5 is selected to be capable of correcting segments in the NR_2 parity bytes when each of the segments contains a maximum of S errors. A segment comprises the i-th systematic byte of each of the N packets.   In one embodiment, a systematic Reed-Solomon code having a minimum distance greater than R_2S is used.

[1038]   The above-described encoding results in NR_2 systematic bytes and $N'R_2$ parity bytes. The $N'R_2$ parity bytes computed by the encoder **206** are provided to an encoder (EC_3) **208**. The encoder **208** encodes the $N'R_2$ parity bytes with the code C_3. The code C_3 is selected so that a packet sent as an element of the code C_3 is decoded correctly with a probability P_{C3} by every destination station. A relationship between a required probability of receiving the message $P_{Message}$, the probability P_{C2}, and the probability P_{C3} is given by the following equation:

$$P_{Message} \approx S \cdot P_{C2} + P_{C3} \tag{10}$$

Therefore, given a reliability requirement for message delivery expressed in terms of $P_{Message}$, Equation (10) is used for selection of the codes C_2 and C_3.

[1039]   The purpose of encoding the $N'R_2$ parity bytes with the code C_3 is to deliver the encoded $N'R_2$ parity bytes **224** from an origination station to a destination station with reliability expressed in terms of P_{C3}. Consequently, there is no restriction on the organization of the encoded $N'R_2$ parity bytes **224**. Therefore, the encoded $N'R_2$ parity bytes **224** may be organized in an arbitrary number of packets. Consequently, in one embodiment, the encoded $N'R_2$ parity bytes **224** form one packet.   In another embodiment, the encoded $N'R_2$ parity bytes **224** are organized into a plurality of packets.

[1040] Referring back to **FIG. 2A**, the output signals of the encoder **204** and the encoder **208** are provided to a transmitter **210**. The transmitter **210** performs processing of the provided signals in accordance with the modulation scheme used. In one embodiment, the modulation is carried out in accordance with the requirements of a wireless communication channel. The transmitter **210** then transmits the N packets provided by the encoder **204** and the packet or packets provided by the encoder **208** over a communication channel **112**. Although a wireless communication channel is shown in **FIG. 2A**, one of ordinary skill in the art recognizes that the communication channel **112** can be wire-like, e.g., a coaxial cable, an optical cable, etc. In such an embodiment, the modulation is carried out in accordance with the requirements of the particular wire-like communication channel.

[1041] A receiver **214** receives the N-packet message and the packet or packets of the encoded N'R$_2$ parity bytes **224** of **FIG. 2D**. The receiver **214** processes the packets in accordance with a demodulation scheme. Generally, an inverse of the modulation process employed by the transmitter **210** is used. The processed packets are provided to a decoder **216**. The decoder **216** decodes each of the N received message packets. As discussed, at most S of the N packets fail to decode. The decoder **216** then decodes the N'R$_2$ parity bytes, and uses the N'R$_2$ parity bytes to recover the non-decoded packets using the method illustrated in **FIG. 3**. The decoded packets are provided to a data sink **218**.

[1042] Referring to **FIG. 3**, in step **302**, a method computes the R$_2$ punctured bytes for each of the N message packets that were correctly decoded. (Thus, the decoder computes at least (N–S)R$_2$ punctured bytes in this manner.) The (N–S)R$_2$ punctured bytes are also the systematic bytes of the Reed-Solomon code. The method then continues in step **304**.

[1043] In step **304**, the packet or packets of the encoded N'R$_2$ parity bytes are decoded. Because the packet or packets were encoded by the code C$_3$, decoding is successful with high reliability. The method then continues in step **306**.

[1044] In step **306**, the remaining SR_2 punctured bytes, which are also the systematic bytes of the Reed-Solomon code, are recovered using the $N'R_2$ parity bytes, using the erasure correction capability of the Reed-Solomon code. An example of the erasure correction capability of the Reed-Solomon code is disclosed in Truong, T.-K., Jeng, J., H., and Hung, K.-CH., Inversionless Decoding of Both Errors and Erasures of Reed-Solomon Code. The method then continues in step **308**.

[1045] In step **308**, the punctured bytes recovered in step **306** now provide enough redundancy to decode all of the packets that were not yet decoded.

[1046] Because the total number of extra bytes transmitted by this scheme relative to the baseline system is $[SR_2(1 + (R_1 + R_{13})/K)]$, the fractional overhead (FO_{SRPB}) relative to the baseline scheme is given as:

$$FO_{SRPB} = (1 + \frac{R_1 + R_{13}}{K}) \cdot (\frac{S}{N}) \cdot (\frac{R_2}{K + R_1}) = (\frac{S}{N}) \cdot (\frac{R_2}{K}) \cdot (1 + \frac{R_{13}}{K + R_1}) \quad (11)$$

[1047] Comparing the results for the disclosed system with the Shared Redundancy System, yields:

$$\frac{FO_{SRPB}}{FO_{SR}} = \frac{R_2}{K} \quad (12)$$

Therefore, for $R_2 \ll K$ the Shared Redundancy System with Punctured Bytes is more efficient than the Shared Redundancy System.

[1048] Table 1 shows the fractional overhead associated with the above-discussed methods for a typical set of parameter values.

	ARQ	Full Redundancy	Shared Redundancy	Shared Redundancy with Punctured Bytes
FO	$P_e/(1-P_e)$	$R_2/(K+R_1)$	(S/N) * (1+R_{13}/(K+R_1))	(S/N) * (R_2/K) *

			$(1+R_{13}/(K+R_1))$	$(1+R_{13}/(K+R_1))$
FO for values: $P_e = 0.4$, K =128, $R_1=0$, $R_2 = 40$, S = 0.2 N	66.67%	31.25%	26.25%	8.2%

Table 1.

Shared Redundancy with Punctured Bytes and ARQ

[1049] In another embodiment, referring back to **FIGS. 2A-D,** the information signal processing by the data source **202**, the encoder **204**, and the encoder **206** may be identical to the processing described above in the "Shared Redundancy with Punctured Bytes" embodiment.

[1050] The output signal of the encoder **204** is provided to a transmitter **210**. The transmitter **210** performs processing of the provided signal in accordance with the processing described above in the "Shared Redundancy with Punctured Bytes" embodiment.

[1051] The receiver **214** at each destination station receives the N message packets and processes the packets in accordance with the demodulation scheme. Such processing is generally achieved by using an inverse of the modulation process employed by the transmitter **210**. The processed packets are provided to a decoder **216**. The decoder **216** decodes the N packets, and determines how many packets failed to decode. Each destination station then informs the origination station about how many packets the destination station was unable to decode. Let S_j denote the number of packets erased by the j-th destination station. Then, it is sufficient that the origination station send $S'R_2$ parity bytes of the Reed-Solomon code, where S' is given by Equation (13):

$$S' = \max(S_j) \qquad\qquad (13)$$

[1052] The S'R$_2$ parity bytes are provided to an encoder **206**. The processing of the S'R$_2$ parity bytes by the encoder **206** and the encoder **208** may be identical to the processing described above in the "Shared Redundancy with Punctured Bytes" embodiment.

[1053] The output signal of the encoder **208** is provided to a transmitter **210**, which transmits the properly modulated signal to the receiver **214**. The receiver **214** processes the packet or packets in accordance with a demodulation scheme, and provides the demodulated packet or packets to the decoder **216**. The decoder **216** then uses the S'R$_2$ parity bytes to recover the non-decoded packets using the method illustrated in **FIG. 3**. The decoded packets are provided to the data sink **218**.

[1054] If S' is considerably lower than S most of the time, then this embodiment is more efficient than the above-described "Shared Redundancy with Punctured Bytes" embodiment.

Modified Shared Redundancy with Punctured Bytes and ARQ

[1055] In another embodiment, the destination stations are configured to determine the number of first punctured bytes necessary to decode a packet that failed to decode when sent as an element of code C$_1$. In accordance with the embodiment, referring to **FIGS. 2A-D,** the information signal processing by the data source **202** and the encoder **204** may be identical to the processing described above in the "Shared Redundancy with Punctured Bytes" embodiment.

[1056] The NR$_2$ parity bytes computed by the encoder **204** are further encoded. Referring to **FIG. 2D**, the i-th parity byte of each of the N packets is combined to form an i-th input data block **220**. Each input data block **220** is provided to a systematic block encoder **206**. The systematic block encoder **206** encodes each input data block **220** by a systematic code C$_4$, having a minimum distance greater than S, resulting in an R$_2$ encoded packets **222**, each packet **222** comprising N systematic bytes and N' parity bytes. In one embodiment, a

systematic Reed-Solomon (RS) code with N' = S, which is guaranteed to have a minimum distance of (S+1), is used. The above-described encoding results in NR_2 systematic bytes and $N'R_2$ parity bytes.

[1057] The output signal of the encoder **204** of **FIG. 2A** is provided to a transmitter **210**. The transmitter **210** performs processing of the provided signal in accordance with the processing described above in the "Shared Redundancy with Punctured Bytes" embodiment.

[1058] The receiver **214** at each destination station receives the N packets and processes the packets in accordance with the demodulation scheme. Such processing is generally achieved by using an inverse of the modulation process employed by the transmitter **210**. The processed packets are then provided to a decoder **216**. The decoder **216** attempts to decode the N packets, and determines, for each non-decoded packet, how many punctured parity bytes are required so that each non-decoded packet is decoded correctly. Each destination station, e.g., the j-th destination station, reports to the origination station R_2 different numbers $S_{j,1}$, $S_{j,2}$, $S_{j,3}$, . . ., $S_{j,R2}$, where $S_{j,m}$ denotes the number of packets that require only the first m punctured parity bytes in order to be decoded correctly by the destination station. Thus, the total number of erased packets for j-th destination station is:

$$S_j \equiv \sum_{m=1}^{R_2} S_{j,m}$$

(14)

[1059] The origination station then selects P_i parity bytes of the i-th RS code for each i = 1,2, .. , R_2, where:

$$Q_i = \max_j [\sum_{m=i}^{R_2} S_{j,m}]$$

(15)

[1060] The selected Q_i parity bytes are provided to the encoder **208**. The encoder **208** encodes the selected Q_i parity bytes with the code C_3. The code C_3 is selected so that a packet sent as an element of the code C_3 is decoded

correctly with a probability P_{C3} by every destination station. A relationship between a required probability of receiving the message $P_{Message}$, the probability P_{C2}, and the probability P_{C3} is given by the following equation:

$$P_{Message} \approx P_{C2} + S \cdot P_{C3} \tag{16}$$

Therefore, given the requirement of message delivery expressed in terms of $P_{Message}$, Equation (16) is used for selection of codes C_2 and C_3.

[1061] The purpose of encoding the Q_i parity bytes by the code C_3 is to deliver the encoded Q_i parity bytes with reliability expressed in terms of P_{C3}. Consequently, there is no restriction on the organization of the encoded Q_i parity bytes. Thus, the encoded Q_i parity bytes may be organized in an arbitrary number of packets. Consequently, in one embodiment, all of the Q_i parity bytes form one packet. In another embodiment, the P_i parity bytes are organized into a plurality of packets.

[1062] **FIG. 4** illustrates a method used by the j-th destination station to recover the erased packets.

[1063] In step **402** the packet or packets containing the selected Q_i parity bytes of the RS code received by the j-th destination station from the origination station are decoded. Because the packet or packets were protected by the code C_3, decoding is always successful. The method continues in step **404**.

[1064] In step **404**, the variable *i* is initiated to the value 1, and compared against R_2. If the value of the variable *i* is smaller than R_2, the method continues in step **406**; otherwise the method continues in step **412**.

[1065] In step **406**, the j-th origination station decoder recovers the punctured byte at the first punctured byte position of each erased packet from the first P_1 parity bytes of the first RS code. This recovery is always possible because $S_j \leq P_1$. The method continues in step **408**.

[1066] In step **408**, the decoder decodes $S_{j,1}$ packets. The method continues in step **410**.

[1067] In step **410**, all the missing punctured bytes for the packets decoded in step **408** are computed. The total number of missing punctured bytes at the second punctured byte position is given by $S_j - S_{j,1} \leq P_2$. The method returns to step **404**.

[1068] In step **412**, the method stops because all packets comprising the message have been computed.

[1069] The total number of extra bytes transmitted by this method relative to the baseline system is:

$$\left(1 + \frac{R_1 + R_{13}}{K}\right) \sum_{i=1}^{R_2} Q_i = \left(1 + \frac{R_1 + R_{13}}{K}\right) \sum_{i=1}^{R_2} \max_j \left[\sum_{m=1}^{R_2} S_{j,m}\right]$$

$$\leq \left(1 + \frac{R_1 + R_{13}}{K}\right) \sum_{i=1}^{R_2} \max_j \left[\sum_{m=1}^{R_2} S_{j,m}\right] = \left(1 + \frac{R_1 + R_{13}}{K}\right) R_2 \max_j \left(S_j\right) \qquad (17)$$

$$= \left(1 + \frac{R_1 + R_{13}}{K}\right) R_2 S'$$

Because this number is smaller than the number of bytes (R_2S') of the previous embodiment, a system in accordance with this embodiment may be more efficient.

[1070] Those of skill in the art would understand that information and signals may be represented using any of a variety of different technologies and techniques. For example, data, instructions, commands, information, signals, bits, symbols, and chips that may be referenced throughout the above description may be represented by voltages, currents, electromagnetic waves, magnetic fields or particles, optical fields or particles, or any combination thereof.

[1071] Those of skill would further appreciate that the various illustrative logical blocks, modules, circuits, and algorithm steps described in connection with the embodiments disclosed herein may be implemented as electronic

hardware, computer software, or combinations of both. To clearly illustrate this interchangeability of hardware and software, various illustrative components, blocks, modules, circuits, and steps have been described above generally in terms of their functionality. Whether such functionality is implemented as hardware or software depends upon the particular application and design constraints imposed on the overall system. Skilled artisans may implement the described functionality in varying ways for each particular application, but such implementation decisions should not be interpreted as causing a departure from the scope of the present invention.

[1072]   The various illustrative logical blocks, modules, and circuits described in connection with the embodiments disclosed herein may be implemented or performed with a General Purpose Processor (GPP), a Digital Signal Processor (DSP), an Application Specific Integrated Circuit (ASIC), a Field Programmable Gate Array (FPGA) or other programmable logic device, discrete gate or transistor logic, discrete hardware components, or any combination thereof designed to perform the functions described herein. A general purpose processor may be a microprocessor, but in the alternative, the processor may be any conventional processor, controller, microcontroller, or state machine. A processor may also be implemented as a combination of computing devices, e.g., a combination of a DSP and a microprocessor, a plurality of microprocessors, one or more microprocessors in conjunction with a DSP core, or any other such configuration.

[1073]   The steps of a method or algorithm described in connection with the embodiments disclosed herein may be embodied directly in hardware, in a software module executed by a processor, or in a combination of the two.   A software module may reside in RAM memory, flash memory, ROM memory, EPROM memory, EEPROM memory, registers, hard disk, a removable disk, a CD-ROM, or any other form of storage medium known in the art. An exemplary storage medium is coupled to the processor such that the processor can read information from, and write information to, the storage medium.   In the alternative, the storage medium may be integral to the processor.   The processor and the storage medium may reside in an ASIC. The ASIC may reside in a user terminal (presumably previously defined broadly).   In the

alternative, the processor and the storage medium may reside as discrete components in a user terminal.

[1074] The previous description of the disclosed embodiments is provided to enable any person skilled in the art to make or use the present invention. Various modifications to these embodiments will be readily apparent to those skilled in the art, and the generic principles defined herein may be applied to other embodiments without departing from the spirit or scope of the invention. Thus, the present invention is not intended to be limited to the embodiments shown herein, but is to be accorded the widest scope consistent with the principles and novel features disclosed herein.

[1075] A portion of the disclosure of this patent document contains material which is subject to copyright protection. The copyright owner has no objection to the facsimile reproduction by anyone of the patent document or the patent disclosure, as it appears in the Patent and Trademark Office patent file or records, but otherwise reserves all copyright rights whatsoever.